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Technical Communication

Reply to Comment on 'Marine GIS: Identification of mesoscale oceanic thermal fronts'

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1. Introduction

We reply to the comment on Valavanis *et al*. (2005) (Marine GIS: Identification of mesoscale oceanic thermal fronts), which appeared in volume 19(10) of the *International Journal of Geographical Information Science* (IJGIS). Critiquing authors argue that Valavanis *et al*. (2005) proposed 'sink' method for front detection is flawed because it is based on an erroneous definition of an oceanic thermal front at the mesoscale level. We welcome their arguments, and we try to clarify them, aiming towards an instructive interchange for IJGIS readership, as well as all authors involved.

2. General discussion

A front is usually a vertically inclined interface between water masses of different properties (mainly salinity, temperature, and chlorophyll-a), where nutrient-rich waters are moved up or trapped in the interface (Largier 1993, Acha *et al*. 2004). Fronts are caused by diverse forcing such as tides, continental runoff, currents convergence, wind, solar heating, bathymetry, etc. There is no agreement about the classification of fronts, but a partial listing would include shelf-break fronts, upwelling fronts, estuarine fronts, plume fronts, and fronts associated with geomorphic features such as headlands, islands, canyons, and seamounts (Mann and Lazier 1996). Under this definition, a front is identified if the along-track gradient exceeds a predefined threshold, and it is significantly greater than the average gradient magnitude in the surrounding region. The observed complicated internal structure of a front, which might comprise several frontal features with enhanced properties gradients, implies that it should be considered a 'frontal zone' rather than 'front' (Fedorov 1986). These points are illustrated in figure 1.

On the other hand, the definition of the term 'mesoscale' is a matter of spatial and temporal scales. For example, if we consider the North Adriatic Sea as the study area, then a front that occupies most of the North Adriatic basin and appears for several months is not a mesoscale within the study area, but it may be well

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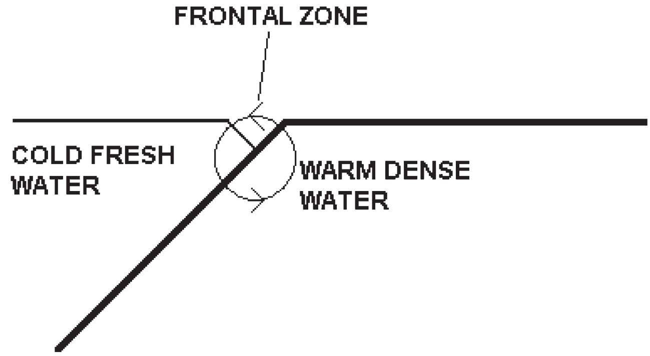

Figure 1. Simple schematic diagram of the frontal zone (as treated by the 'sink' method) is shown. Water circulation patterns result in moved up and/or trapped nutrient-rich waters in the frontal zone.

considered mesoscale within the Central Mediterranean area or the whole Mediterranean basin in a timescale of a year. If the whole of an oceanic process describes the synoptic picture of the oceanography of a study area, smaller oceanic features (associated with the main oceanic process) describe the sub-synoptic, or mesoscale oceanography of the area.

Regarding the proposed 'sink' method, it is mainly based on two ESRI's ArcGIS macro routines, named 'flowdirection' and 'sink' (ESRI, 1994). The 'flowdirection' macro includes the concept of gradient in cell values (change in *z* value) because the direction of flow is determined by finding the direction of steepest descent from each cell. This is calculated as 'drop=change in *z* value/distance$\times$100' on a 3×3 cell window and there are eight discrete and valid flow angles (Jenson and Domingue 1988). Then, the 'sink' macro identifies sink cells based on 'direction of flow' or 'drop' values. A sink is a cell or set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction grid. This can occur when all neighbouring cells have higher values than that of the processing cell, or when two cells flow into each other, creating a two-cell loop (Mark 1988).

When this concept is applied to an AVHRR SST satellite image for the identification of fronts, the sink method identifies those areas that are characterized by the attribute of front where the temperature is lower exactly on the frontal interface, while SST is more homogeneously distributed around the frontal interface. This is true in fronts as oceanic process when two different water masses meet. The whole concept functions on a 3×3 cell window, and this is the reason why the sink method targets transient, small, thermal, and productivity-enhancing fronts that occur in scales of a few kilometres and sufficient to be depicted in monthly averaged SST satellite images. In addition, the measurement of chlorophyll-a levels in the frontal interface (through the use of SeaWiFS or MODISA Chl-a images) depicts the characteristic of front where nutrient rich waters are moved up or trapped in the frontal interface between two water masses.

3. Application of 'sink' method to Istrian Front (North Adriatic Sea)

The Istrian front is a basin-wide front with extensive presence throughout winter months in North Adriatic Sea (Cushman-Roisin and Korotenko 2005). It is a salinity–temperature front between cold freshwater of Po River outflow into the North Adriatic and the warm saline waters of the East Adriatic Current that brings

Levantine Intermediate Water and Ionian Surface Water into the Adriatic. In cases of clear Bora events (strong winter north-easterly winds), North Adriatic oceanography is characterized by the intensification of Istrian front and a number of gyres, fronts, meanders, etc. (e.g. Book *et al.* 2005). The productivity levels of North Adriatic Sea depend on the riverine water discharge of Po River (Vilicic *et al.* 2007) and during winter they do not provide strong signature signal in colour satellite imagery (Lee 2003).

The 'sink' method in the case of Istrian front identifies only the adjacent, smaller (named 'mesoscale'), productive thermal fronts associated with adjacent eddies and small gyre formations resulting from the Istrian front's circulation patterns and other smaller-scale oceanic processes (figure 2). Additionally, the Istrian front is a salinity–temperature front with no high productivity signal. The sink method requires high productivity levels in the frontal interface due to accumulation of phytoplankton to the convergence zone of two different water masses. It does this by calculating Chl-a values from SeaWiFS or MODISA satellite images inside and outside the frontal interface.

If the whole of Istrian Front and associated gyres describe the synoptic picture of the oceanography of the Northern Adriatic, smaller oceanic features describe the

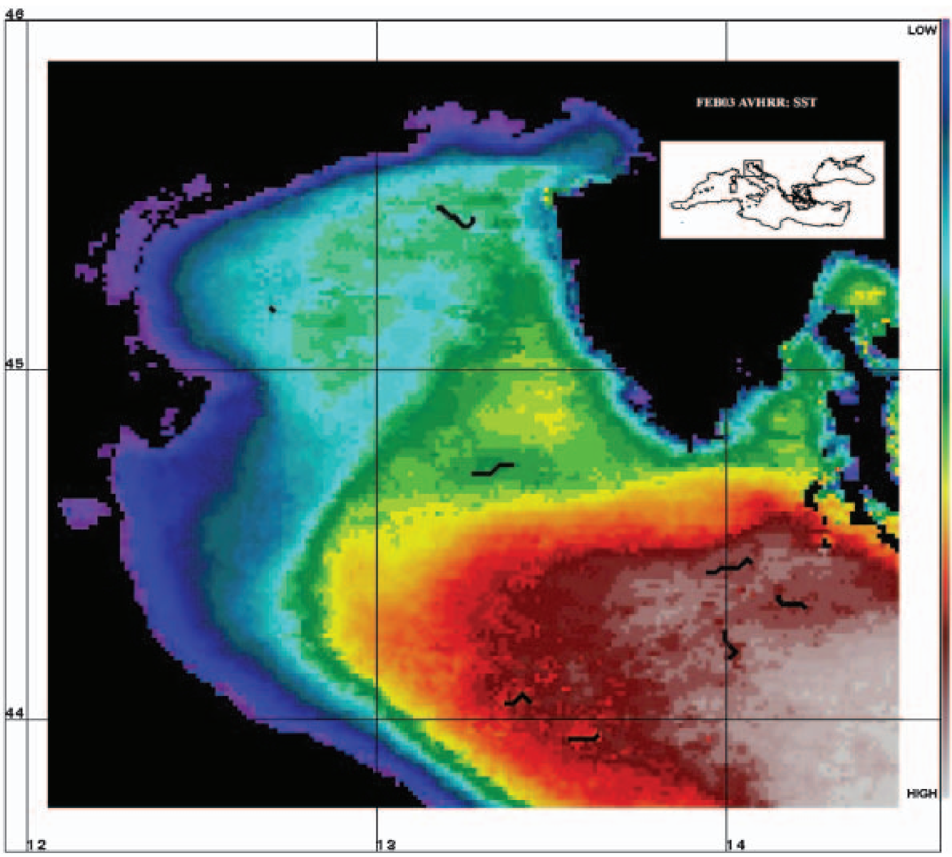

Figure 2. Monthly averaged AVHRR SST of February 2003 for North Adriatic Sea. Although the Istrian Front is well depicted at the centre of the image (narrow region in yellow), the 'sink' method identifies smaller-scale, thermal and productivity-enhancing fronts only (black lines).

sub-synoptic, or mesoscale oceanography of the area. In our initial contribution, we use the term 'mesoscale' exactly with this sense targeting thermal and productivity-enhancing small fronts that are depicted in monthly satellite images.

4. Concluding remarks

Suffice it to say, the 'sink' method identifies the attribute of the frontal zone in which phytoplankton-rich cold waters are trapped in the frontal zone. It cannot identify large-scale fronts where the frontal zone of different water masses occupies areas of tenths of kilometres. In such cases, gradient methods are preferred due mainly to the input of a threshold in rate of change in SST values as well as the larger analytical window (Ullman and Cornillon 2000) or threshold input using the ArcGIS 'slope' function (ESRI, 1994).

In addition, results of the 'sink' method depend on the spatial resolution of the input SST and Chl-a satellite images (e.g. AVHRR SST of 1.2 km, MODISA Chl-a of 4 km and SeaWiFS Chl-a of 9 km) due to its small analytical window (3×3 pixels).

Finally, Valavanis *et al*. (2005) use wind data to explain the identification of fronts, and we would agree that the use of detailed CTD-like data could be the ultimate ground-truth procedure for the validation of the 'sink' method results.

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